

# A REEMERGENCE DEVICE FOR THE POSTANESTHESIA CARE UNIT

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**Abstract**—Hypercapnia is frequently used to accelerate emergence from anesthesia in the OR, but not in the post anesthesia care unit (PACU). To this end, a reemergence device has been proposed that will take advantage of hypercapnia to reduce recovery time and number of adverse clinical events experienced in the PACU. In order to design a device capable of meeting the wide range of breathing patterns exhibited by patients under sub-anesthetic levels of anesthesia, a simulation package was developed to model gas exchange during rebreathing. Using this model the user is able to manipulate variables such as tidal volume, breathing rate, metabolic rate, reservoir volume, supplemental  $O_2$  rate, etc. and view the resulting gas fractions of  $O_2$ ,  $CO_2$ , and  $N_2$  in the lungs over time.

## INTRODUCTION

THE cardiovascular and respiratory system work in tandem to provide the necessary gas exchange for cellular metabolic activity throughout the body. The respiratory system exchanges  $O_2$  and  $CO_2$  between the atmosphere and blood; the circulatory system delivers the  $O_2$  to cells throughout the body and transports  $CO_2$ —a byproduct of cellular respiration—from the cells back to the lungs. When  $CO_2$  levels fluctuate, such as when metabolic activity changes, the cardiovascular and respiration systems are modified accordingly to compensate. For example, if the arterial partial pressure of  $CO_2$  ( $Pa_{CO_2}$ ) rises, respiration will increase and vasodilation will occur, increasing blood flow and gas exchange in order to flush the body of excess  $CO_2$ . When  $Pa_{CO_2}$  is reduced, the opposite occurs. In an anesthesia setting, this relationship is frequently taken advantage of.

Induced hypercapnia, or elevated  $Pa_{CO_2}$ , is often used to accelerate a patient's recovery from anesthesia[1], [2]. Anesthetic vapors can be removed in the same way that excess  $CO_2$  is flushed from the body. Recently, the FDA approved a device, called the QED-100, that accomplishes this task during the emergence phase of anesthesia in the OR[3]. This device incorporates a rebreathing reservoir to induce hypercapnia and a charcoal filter to soak up expelled anesthetic gases. Studies have shown that the QED-100 is capable of reducing emergence times by approximately 55%[3], [4], [5]. However, as mentioned, this device is only used in the

OR until the patient is conscious and able to maintain a patent airway, after which they are moved to PACU to continue recovery until discharge criteria are met.

The incidence of adverse clinical events is much higher in the PACU than the OR. As a patient becomes more alert in the PACU, a greater awareness of pain is evident, so additional analgesics are often administered, which can react synergistically with trace amounts of anesthetic and cause loss of consciousness, difficulties breathing, etc. Studies have shown that of 42,000 patients monitored, 23–24% experienced complications in the PACU, while only 3.8–5.1% encountered difficulties in the operating room[6], [7], [8]. The need for a faster and safer recovery from anesthesia in the PACU is apparent.

To this end, a device has been proposed for use in the PACU that will take advantage of hypercapnia in order to reduce recovery time and the number of adverse clinical events. The goal is to integrate the functionality of the QED-100 with a standard oxygen mask; however, the design criteria for such a device is quite demanding. In contrast to the OR where ventilation is performed and monitored closely by an anesthesia machine, a patient in the PACU can on their own—albeit an irregular, shallow, and slow breathing pattern due to sub-anesthetic levels of drug still present in their body. In this state they are at greater risk of hypoxia, and often supplemental oxygen is given to compensate. The use of a hypercapnia-inducing device, like the QED-100, in this setting would further increase the risk of hypoxia. Therefore, as part of the recovery device being designed for the PACU, a port for supplemental oxygen will be included. This presents another problem: addition of oxygen may dilute the rebreathed air sufficiently as to diminish and even obliterate the hypercapnic effect of rebreathing. Hence, the design of the recovery device must be robust in its ability to induce hypercapnia while avoiding hypoxia for a wide range of breathing patterns.

To understand and optimize the relationship between rebreathing and oxygen supplementation, it was suggested that a model be created to simulate rebreathing with oxygen supplementation. The model had to be capable of simulating various breathing patterns while tracking gas concentrations over time. As a first step in designing a recovery device for the PACU, this paper

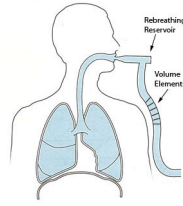


Fig. 1. Model of a patient with rebreathing device as simulated. The tube represents the rebreathing reservoir, and the volume elements are indicated as segments of the tube. Adapted from Silverthorn, pg 562[9]. Arrows and labels added separately.

describes the model being designed to simulate the proposed device.

### METHODS

The simulation package was programed using Matlab (Mathworks, Natick, MA). The model was broken into two systems: a breathing model—to drive the system, and a rebreathing reservoir, which causes the change in gas concentrations over time.

The breathing simulation was defined by the relationship between lung compliance, airway resistance, and relative pressures between the atmosphere and lungs. The first order relationship between these parameters was estimated using Eurler's method as follows,

$$P(i+1) = P(i) + \frac{\Delta t \cdot Q(i)}{C} \quad (1)$$

$$V(i+1) = V(i) + \Delta t \cdot Q(i) \quad (2)$$

$$Q(i) = P(i)/R \quad (3)$$

where  $P$  is pressure,  $Q$  is flow,  $C$  is compliance,  $V$  is volume,  $R$  is resistance,  $\Delta t$  is the time increment, and  $i$  is a particular step in time. The user was able to modified each of these parameters so that various types of breathing patterns could be simulated.

During inspiration, the flow of air was considered to be constant, comparable to the function of a ventilation machine. Expiration began when a defined tidal volume was reached. The flow of air during expiration was characterized by the compliance and resistance of the lungs as defined in equations 1, 2, and 3.

In order to simulate the gas exchange within the rebreathing reservoir, the space was divided into small volume elements (Figure 1). The math then became a simple accounting problem where gas exchange between each volume element was calculated and tracked through each step in time. The user was able to modify parameters relating to the rebreathing reservoir, which included reservoir volume, number of volume elements, location of supplement oxygen port, and the flow rate of supplemental oxygen.

Figure 1 shows a representation of a patient with the rebreathing device as simulated. Beyond the parameters already mentioned, the user could also define the number of breaths to simulate, the functional residual volume of the lungs, tidal volume, the rate of metabolic consumption of  $O_2$  and production of  $CO_2$ , the relative gas fractions of the atmosphere, and the initial gas fractions in the lungs and rebreathing reservoir. Thus nearly any combination of patient breathing pattern and rebreathing reservoir could be simulated.

### RESULTS

A screenshot of the simulation model is shown in Figure 2. This particular simulation was carried out for 100 breaths at 10 breaths per minute, which equalled approximately 10 min as shown in the bottom graph. The top three graphs show the pressure, volume, and flow curves for one minute of the simulation, which allows the user to observe the details of each breath. The three panels on the left are where the user changes the various parameters of the system before running the next simulation.

From the pressure graph on top it can be seen how the pressure rises linearly during inspiration and then decays exponentially during expiration. This was expected since, as was mentioned, flow during inspiration was considered to be constant, as evidenced by the plateau in the flow curve. The curve during expiration follows the first order relationship between pressure, lung compliance, airway resistance, and flow (Equations 1, 2, and 3). The curves appear similar to the curves seen on a typical ventilator.

The bottom graph shows the gas fractions in the lung with respect to time. Notice how the  $CO_2$  and  $O_2$  curves rise while flushing out the  $N_2$ . This is similar to the desired result of the device. Oxygen needs to remain high to prevent hypoxia, but not so high as to dilute  $CO_2$  and loose hypercapnic effects. It should be noted that the axis on the right corresponds to the  $CO_2$  gas fraction; those on left correspond to  $O_2$  and  $N_2$ . The zigzag nature of the curves represents the inspiration and expiration cycles. This particular simulation places the supplemental oxygen port in or near the face mask and supplies 5 L/min of  $O_2$ .

### DISCUSSION

It should first be mentioned that work is currently being done to verify this simulation using a bench test model so that, presently, the validity of this model is unknown—except for the qualitative observations already made. That being said, several speculations can

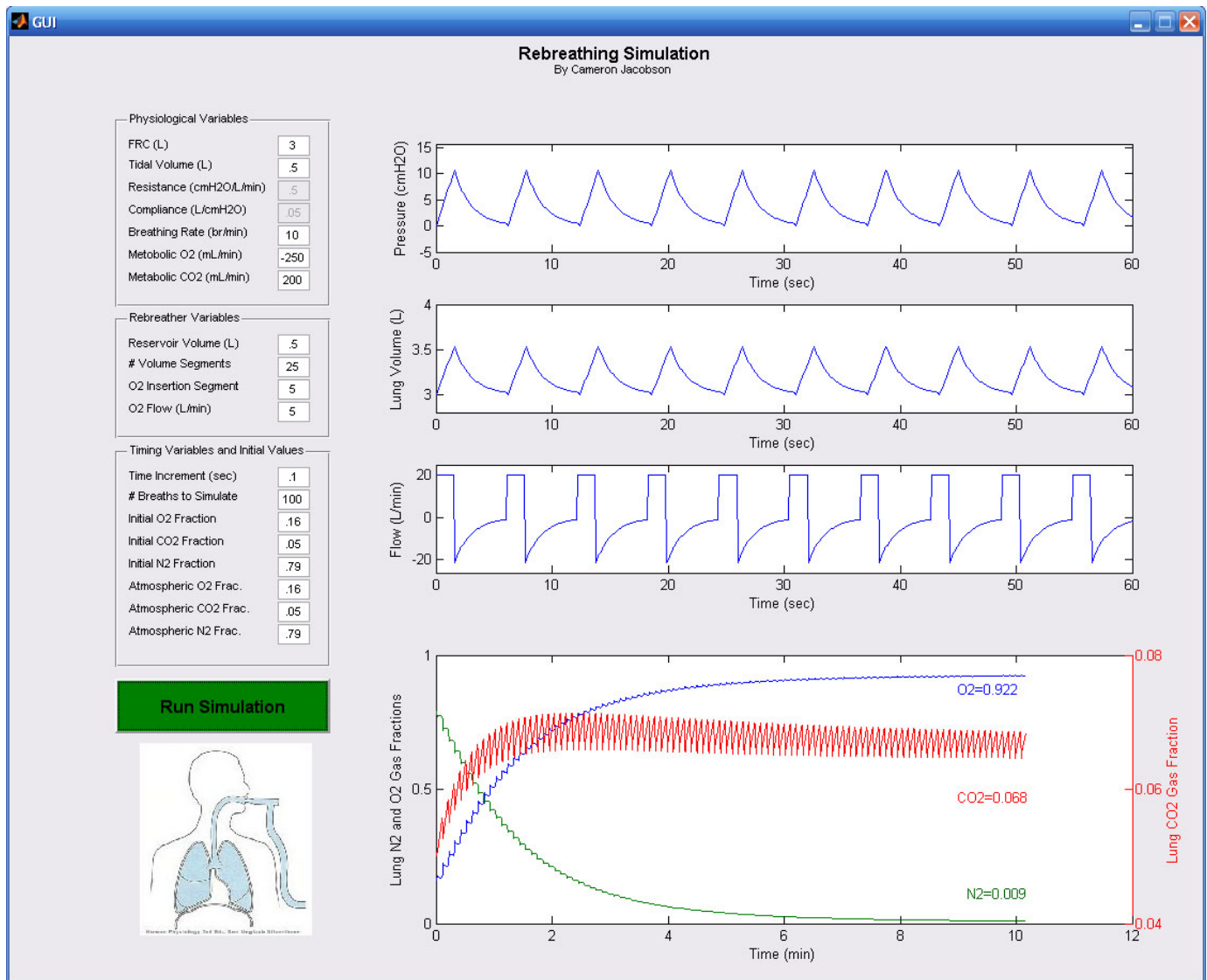


Fig. 2. Screenshot of simulation. One minute of the pressure, volume, and flow graphs are displayed on top. The resulting gas fractions in the lungs for a 10 min simulation are shown in the bottom graph. Notice that the axis on the right is for the  $\text{CO}_2$  curve. The panels on the left are for changing the various parameter of the simulation.

still be made regarding the limitations of the present model.

The curves presented in Figure 2 appear to be similar to those expected using a ventilation machine; however, in the PACU a patient is breathing spontaneously. The inspiration curve would appear less linear and more first order, like the expiration curve. It needs to be determined whether the error that is introduced by assuming a constant flow during inspiration is significant enough to invalidate the model.

It is known that  $\text{PaCO}_2$  affects respiration[10]. This model does not take into account the fact that respiration rate and depth may change as hypercapnia sets in. Also, this model assumes a regular, consistent breathing rate throughout the duration of the simulation. In reality, a pa-

tient's breathing patterns can vary from breath to breath. Most likely the simulation will need to be modified in order to test variability in the breathing pattern.

The simulation also assumes no leakage between the oxygen mask and the face of the patient. Leakage can greatly influence the effect of rebreathing. This too could easily be incorporated into the simulation. Both simulation and bench tests will need to be done to quantify the effect of leakage so that the device can be designed to account for a certain degree of leakage.

Another assumption of the model is perfect mixing of the gases: during each step in time it is assumed that when a small volume of gas moves from one volume segment to the next the gases mix perfectly so that the exiting gas takes on the new gas fraction. This

assumption may be negligible, especially if the volume element is sufficiently small, but worthy of note if the volume element is increased.

Ideally the best simulation would be one that could include variables that were defined as close to reality as possible, but unfortunately this is not always possible. Certain assumptions have to be made in order to make the computations manageable. Sometimes those assumptions can introduce significant errors into the model, which can then hopefully be tested and verified in a real experiment. Such is the case with this model. As mentioned, bench tests, using a mechanical lung, are currently being conducted to validate the model.

### CONCLUSIONS

The work done thus far in creating a model to simulate rebreathing with oxygen supplementation has been successful in meeting the initial goals of the design process and serves as a base for future work. Several assumptions need to be tested, such as constant inspiratory flow, the continuous, non-varying breathing pattern, and the effects of hypercapnia on respiration. Aside from those obvious limitations, the model also needs to be validated with bench tests, which have begun.

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